TITLE OF THE INVENTION

PROFILE MEASURING METHOD AND MEASUREMENT APPARATUS
USING INTERFERENCE OF LIGHT

CROSS-REFERENCE TO RELATED APPLICATIONS

5   This application is based upon and claims the
benefit of priority from the prior Japanese Patent
Application No. 2001-267786, filed September 4, 2001,
the entire contents of which are incorporated herein by
reference.

10   BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a profile
measuring method and apparatus for use in the field of
manufacturing of an ultra high degree precision machine
15 components, the field of managing their quality and/or
the field of measuring them, the surface profile of
a preformed product, such as a magnetic recording
component and an LSI substrate, or a liquid crystal
substrate for computers, the method and apparatus
20 capable of accurately measuring, by uses of the
interference of light, with the ultra high degree
precision ranging from several nanometers to several
hundreds of micrometers.

2. Description of the Related Art

25   Techniques for measuring the shapes, in
particular, surface profiles of industrial products,
are important industrial techniques, and profile

measurement apparatuses employing various measuring methods are now being used. In particular, profile measurement apparatuses use of the interference of light capable of non-contact measurements are widely used. However, most apparatuses of this type are not made in JAPAN.

In general, the profile measuring methods by uses of the interference of light, white light is applied to the surface of a sample through a band-pass filter, interference light formed by light reflected from the surface of a sample and light reflected from a reference surface (a reference mirror) is picked up by a camera, and an image output from the camera is subjected to image processing (the image output is analyzed). In the profile measuring methods for acquiring interference light include, for example, the phase shift method or multipoint simultaneous pickup method. The phase shift method include various types of making an optical-path difference for the acquisition of interference light. Further, there are various types of output image processing methods.

Wyco Corporation (USA), for example, provides a profile measurement apparatus in which an interference phase is obtained for a smooth surface having an unevenness of about several microns, using the phase shift method that employs a shift amount of $\pi/2$, while the profile of a surface having a greater

unevenness is obtained from the peak position of
an envelope indicative of variations in the sine wave
of an interference signal appearing when an optical-
path difference is changed.

5   In the Wyco profile measurement apparatus, to
enable both a smooth surface and a rough surface to be
measured, phase shifting is executed in units of less
than π, such as $\pi/2$ or $\pi/3$. A number of interference
images are picked up by a two-dimensional camera, and
10   phase data of each pixel of the camera is obtained from
a signal output from the camera, using the phase shift
algorithm. Further, the envelope of variations in the
sine wave of an interference signal is extracted from
the signal, thereby calculating the profile of the
15   surface.

Zygo corporation (USA) provides a measurement
apparatus for picking up an interference image using
a shift amount of $\pi/2$, and simultaneously extracting
interference contrast data and phase data, using a data
20   analysis in frequency domain.

In the Zygo profile measurement apparatus and
method, it is not necessary to measure the peak
position of an envelope for each pixel, and both
a smooth surface and a relatively rough surface with
25   a step can be measured using the same data processing
method. Further, this method incorporates a technique
for minimizing the required memory capacity.

In addition to the above-described two measuring apparatuses, a further method has been proposed. In this method, the shape of an envelope of variations in the sine wave of an interference signal, which appears when an optical-path difference is changed, is estimated from a small number of sampling points (in terms of an amount of shift (shift amount) in the phase shift method, image pickup is executed in units of about 10π), using a band-pass type sampling theorem, thereby extracting the peak position and obtaining a surface profile.

Moreover, a method for increasing measurement speed has been proposed, which employs multipoint simultaneous image pickup using a confocal microscope effect and a microlens array (Journal of the Japan Society for Precision Engineering, Vol. 64, No. 7, pp 1022 to 1028, 1998).

In the case of using light interference based on light of a wavelength λ, if an optical-path difference is differed with $\lambda \times n'$ (n' is an integer), the intensity of interference light is substantially identical for different values of n', and hence the optical difference cannot be correctly determined. Accordingly, a sample that has a rough surface with discontinuous surface level variations cannot be measured simply by a method for obtaining a phase value.

In the aforementioned Wyco profile measurement apparatus, phase shifting is executed in units of less than π, such as $\pi/2$ or $\pi/3$, and a number of light interference images are picked up by a two-dimensional camera. In this case, usually, about 1/30 second is required to transfer data corresponding to one image from the camera to a computer, and the speed, at which the optical-path difference of the interferometer is changed, is set to, at maximum, $(\lambda/4)/(1/30 \text{ sec.})$. In other words, if a phase shift amount is just $\pi/2$, the image pickup operation must be executed four times in order to change the optical-path difference by one wavelength. This means that the interferometer is of a reflection type, and the movement speed of an incorporated movable table is about 2.0 μm/sec., and much time is required for measuring a rough surface.

In this measuring method, even if a high-speed camera is used to increase the transfer rate of image data, much time is required for data processing since the amount of image data itself cannot be reduced, thereby making it difficult to considerably increase the measurement speed.

Furthermore, in the Zygo measuring method and measurement apparatus, a phase shift amount employed in its three-dimensional profile measuring method is about $\pi/2$, as in the Wyco apparatus, and hence it is

. difficult to significantly increase the measurement
speed.

On the other hand, in the method in which the
shape of an envelope of variations in the sine wave of
5   an interference signal, which appears when an optical-
path difference is changed, is estimated from a small
number of sampling points (in terms of a shift amount
in the phase shift method, image pickup is executed in
units of about 10π), using a band-pass type sampling
10   theorem, thereby extracting the peak position and
obtaining a surface profile, the time required for
measurement can be shortened (the measurement speed can
be increased), but the measurement precision is about
1/10 to 1/100 of that of the phase shift method.

15   The other method, which employs multipoint
simultaneous image pickup using a confocal microscope
effect and a microlens array, merely provides
a measurement precision as low as that obtained by
a microscope using confocal focusing (confocal
20   microscope).

BRIEF SUMMARY OF THE INVENTION

It is the object of the invention to provide
a profile measurement apparatus and method for
measuring, at high speed and in a non-contact manner,
25   the surface profile of a to-be-measured object with
a precision as high as that of the phase shift method.

According to an aspect of the present invention,

there is provided a profile measuring method of calculating, using a phase shift method, a phase value of an interference image formed by a light beam reflected from an object and a light beam reflected

5   from a reference mirror, thereby obtaining an optical path difference from the calculated phase value and obtaining a profile of the object from the optical path difference, comprising: emitting, to the object, two flash light beams, having wavelengths slightly

10   different from each other, with a predetermined interval t_1 therebetween; and picking up, using a camera, interference light formed by light beams reflected from the object and a light beam reflected from the reference mirror, while moving the object in

15   a direction, in which the two flash light beams are directed, in units of intervals t_2 at which each of the two flash light beams is cyclically emitted, a phase shift amount corresponding to a movement amount of the object at a time being set to a value falling within a

20   range of $2n\pi \pm \pi/2 \pm \pi/4$.

According to an other aspect of the present invention, there is provided a profile measurement apparatus comprising: a first flash light source which emits a flash light beam of a first wavelength; a

25   second flash light source which emits a flash light beam of a second wavelength, different from the first wavelength, with an interval t_1 from the light beam of

the first wavelength; a movement table which moves an
object in a direction in which the flash light beams
from the first and second flash light sources are
directed to the object; a translucent mirror which

5   diverges, to a reference mirror, part of the two flash
light beams emitted from the first and second flash
light sources and directed to the object, the
translucent mirror returning, to an original route,
light reflected from the reference mirror; a camera

10   which picks up, as an image, interference light formed
by light reflected from the object and light reflected
from the reference mirror; a table control section
which moves the movement table by a predetermined
distance in synchronism with an interval t_2 between

15   successive emissions of light from the first and second
flash light sources; and an image processing unit which
selects an image signal with a maximum amplitude from a
plurality of images output from the camera when the
movement table has been moved by the predetermined

20   distance in synchronism with the interval t_2, thereby
determining an optical path difference on the basis of
a phase difference between two interference images
created by the two flash light beams emitted from the
first and second flash light sources when the camera

25   has picked up the image signal with the maximum
amplitude, and also on the basis of phase values of the
interference images assumed when the camera has picked

up the image signal with the maximum amplitude.

According to a still other aspect of the present invention, there is provided a profile measurement apparatus comprising: a first flash light source which emits a flash light beam of a first wavelength; a second flash light source which emits a flash light beam of a second wavelength, different from the first wavelength, with an interval t_1 from the light beam of the first wavelength; a movement table which moves an object in a direction in which the flash light beams from the first and second flash light sources are directed to the object; a translucent mirror which diverges, to a reference mirror, part of the two flash light beams emitted from the first and second flash light sources and directed to the object, the translucent mirror returning, to an original optical path, light reflected from the reference mirror; a camera which picks up, as an image, interference light formed by light reflected from the object and light reflected from the reference mirror; a table control section which moves the movement table by a predetermined distance in synchronism with an interval t_2 between successive emissions of light from the first and second flash light sources; and an image processing unit which selects an image with a maximum amplitude from a plurality of images output from the camera each time the first and second flash

light sources emit their respective light beams with the interval t_1 interposed therebetween, and also each time the movement table is moved by the predetermined distance in synchronism with the interval t_2, the image

5 processing unit then calculating an optical path difference from two interference images formed by the two light beams emitted from the first and second flash light sources and reflected from a surface of the object, the image processing unit calculating

10 respective optical path differences at the points, thereby determining a surface profile of the object on the basis of phase values of the two flash light beams emitted from the first and second flash light sources when the camera has picked up an image signal with a

15 maximum amplitude from the output images at each of the points of the to-be-measured area of the object.

Additional objects and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may

20 be learned by practice of the invention. The objects and advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out hereinafter.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

25 The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate embodiments of the invention, and together

with the general description given above and the
detailed description of the embodiments given below,
serve to explain the principles of the invention.

5   FIG. 1 is a schematic view illustrating an example
of a structure of a profile measurement apparatus
according to the embodiment of the invention;

FIG. 2 is a schematic view useful in explaining
the interval t_1 between adjacent light beams of
wavelengths λ_1 and λ_2 emitted from two light sources
10   incorporated in the profile measurement apparatus of
FIG. 1, and the interval t_2 between the light beams
with the wavelength λ_1 (or λ_2);

FIG. 3 is a schematic view useful in explaining
that an optical-path difference is zero at different
15   time points in different sampling points when an object
is moved by vertically moving an X-Y table incorporated
in the profile measurement apparatus of FIG. 1;

FIG. 4 is a schematic view illustrating variations
in the intensity of interference light caused by
20   variations in optical-path difference that occur when
the X-Y table is vertically moved, and the timing for
the camera to pick up the interference light;

FIG. 5 is a schematic view illustrating the phase
value of light of each wavelength at each optical-path
25   difference shown in FIG. 4;

FIG. 6 is a schematic view useful in explaining
the phase difference of light beams of the wavelengths

at each optical-path difference shown in FIG. 4;

FIG. 7 is a schematic view illustrating a light intensity corresponding to an image number j for a certain pixel, and an amplitude signal (an amplitude change is obtained by summing up the amplitudes of the light beams of the wavelengths λ_1 and λ_2);

FIG. 8 is a schematic view illustrating a amount of shift (shift amount) α in the phase of light of each wavelength and a phase difference between light of the wavelengths, assumed before and after a k-th image, having the maximum amplitude in FIG. 7, is picked up (broken curve a indicates α/π of the light beam of the wavelength λ_1; broken curve b indicates α/π of the light beam of the wavelength λ_2; ϕ_{12} indicates (the phase value of the light beam of the wavelength λ_1 - the phase value of the light beam of the wavelength λ_2)$/\pi$);

FIG. 9 is a schematic view useful in explaining a k-th image signal with a maximum amplitude calculated for each pixel;

FIG. 10 is a schematic view illustrating an optical path difference assumed when the k-th image has been picked up (since the value of k varies between different pixels, discontinuous optical path differences are obtained even if a smooth surface is measured);

FIG. 11 is a schematic view useful in explaining

a final three-dimensional profile calculated from the
image number k shown in FIG. 9, the optical path
difference shown in FIG. 10, and the movement amount of
the X-Y table (this smooth figure indicates that the

5   method can measure correctly surface profiles of the
object involving a step, since data correction is not
executed in the X or Y directions); and

FIG. 12 is a schematic view useful in explaining
a surface profile obtained only using the known phase

10   shift method.

DETAILED DESCRIPTION OF THE INVENTION

The embodiment of the invention will be described
in detail with reference to the accompanying drawings.

As shown in FIG. 1, a profile measurement

15   apparatus 1 includes a to-be-measured object retaining
section 2 for retaining a sample, i.e. a to-be-measured
object O; a light transmitting system 3 for emitting
light of predetermined wavelengths to the object
retaining section 2; a light receiving system 4 for

20   receiving light (interference light) reflected from the
object retaining section 2; an interference section 5
interposed between the light transmitting and receiving
systems 3 and 4 and functioning as a known
interferometer; and an image processing unit 6 for

25   processing an image signal output from the light
receiving system 4 and outputting a measurement result
indicative of the surface profile of the object.

The object retaining section 2 includes an X-Y
table 21 for moving a sample or object O in two
directions (X-axis and Y-axis directions) perpendicular
to each other; a vertical movement mechanism 22 for

5 moving the X-Y table 21 in a Z-axis direction (vertical
direction) perpendicular to the X-axis and Y-axis
directions; and a table control section 23 for causing
the Z-directional movement of the vertical movement
mechanism 22 to be kept at a constant speed. The image

10 processing unit 6 can control the table control
section 23. The table control section 23 may be
integrated with the image processing unit 6. Further,
if a to-be-measured portion of the object O can be set,
the X-Y table 21 may be moved manually in the X- and/or

15 Y-direction.

The light transmitting system 3 includes first and
second flash lamps 31 and 32 for substantially
simultaneously emitting white light beams or light
beams of predetermined wavelengths (actually with

20 a predetermined slight interval t_1 interposed
therebetween, which will be explained in more detail
with reference to FIG. 2); first and second collimator
lenses 33 and 34 for converting light beams, emitted
from the flash lamps 31 and 32, into parallel light

25 beams, respectively; a first band-pass filter 35 for
passing therethrough a light component of a first
wavelength λ_1 contained in the parallel light beam

passing through the first collimator lens 33; a second
band-pass filter 36 for passing therethrough a light
component of a second wavelength λ_2 slightly different
from the first wavelength λ_1 and contained in the

5   parallel light beam passing through the second
collimator lens 34; a first translucent mirror 37 for
synthesizing the two light components of the first and
second wavelengths λ_1 and λ_2 respectively passing
through the band-pass filters 35 and 36; a second

10   translucent mirror 38 for guiding the light,
synthesized by the first translucent mirror 37,
toward the object O placed on the object retaining
section 2; and an objective lens 39 for imparting
predetermined convergence to the light guided through

15   the second translucent mirror 38, thereby converging
it onto the object O. The wavelengths of the light are
$\lambda_1 = 540$ nm and $\lambda_2 = 575$ nm. The two flash lamps 31
and 32 are, for example, Xe (xenon) lamps.

       The light receiving system 4 includes a relay lens

20   41 for imparting a predetermined image-forming
characteristic to the light (interference light)
reflecting from the object O and passing through the
objective lens 39 of the light transmitting system 3;
and a camera 42 for picking up the interference light

25   (reflected light) with the predetermined image-forming
characteristic supplied by the relay lens 41.

       The light reflected from the object O and returned

to the objective lens 39 is separated, by the second
translucent mirror 38 of the light transmitting system
3, from the light of the wavelengths λ_1 and λ_2 emitted
from the first and second flash lamps 31 and 32 to the
5   object O.

The camera 42 is not limited to any special one.
It is sufficient if the camera 42 has a high-speed
double exposure function that enables the camera to
simultaneously pick up two interference images formed
10   with a slight interval of about 1 msec., at maximum,
more preferably, 200 nsec. to 50 microsec., and most
preferably, 10 microsec. For example, a high-speed
image measurement camera (C7300-10-12NRP) produced by
Hamamatsu Photonics Corporation can be used as the
15   camera 42.

The interference section 5 forms a known
interferometer, and includes a third translucent mirror
51 interposed between the second translucent mirror 38
and the object O for separating part of light directed
20   from the second translucent mirror 38 to the object O;
and a reference mirror 52 located at a position at
which the distance of the mirror 52 to the translucent
mirror 51 is identical to or close to the distance
between the object O and third translucent mirror 51
25   (or second translucent mirror 38). The interference
section 5 causes the light beams of the wavelengths λ_1
and λ_2 reflected from the object O to interfere with

each other to provide light that contains surface
profile features of the object O.

The image processing unit 6 is formed of,
for example, a personal computer, and is configured to
5   process, according to a predetermined rule, an image
signal corresponding to light reflected from the
object O, i.e., interference light, picked up by
the camera 42, thereby analyzing or patterning it.
If an image signal output from the camera 42 is
10   an analog signal, an A/D converter (not shown) or
predetermined image processing software may be used.

Although in the above-described configuration, two
light beams from the light transmission system 3 are
deflected by the second translucent mirror 38, and
15   light reflected from the object O (interference light)
is guided to the camera 42 via the second translucent
mirror 38, the optical elements, two flash lamps and
camera, may be located at any position, as long as the
flash lamps can emit two light beams to the object O
20   and the camera can receive interference light formed by
the light reflected from the object O and the light
reflected from the reference mirror 52.

A description will be given of an example of
a procedure for measurement the surface profile of the
25   object O, using the profile measurement apparatus 1.

First, the object O is fixed on the X-Y table 21.
The X-Y table 21 and vertical movement mechanism 22 are

moved by respective predetermined amounts to set
the object O so that the distance between the
to-be-measured portion (range) of the object O and the
third translucent mirror 51 is substantially identical

5   to the distance between the reference mirror 52 and
third translucent mirror 51 (second translucent
mirror 38). In other words, the distance between
a substantially central portion of the thickness of
the object O and the mirror 51 is set identical to

10   the latter distance.

Subsequently, the first and second flash lamps 31
and 32 are made to substantially simultaneously emit
light beams as shown in FIG. 2 (for example, they emit
their respective light beams with a slight interval t_1

15   of about 1 msec., at maximum, preferably, 200 nsec. to
50 microsec., and more preferably, 10 microsec.).
These beams are converted by the collimator lenses 33
and 34 into parallel light beams, and then, light beams
of the wavelengths λ_1 and λ_2 are formed via the band-

20   pass filters 35 and 36. These beams are synthesized by
the first translucent mirror 37 (instant illumination
light of two wavelengths (λ_1 and λ_2) is formed).

This light (λ_1 and λ_2) is deflected by the second
translucent mirror 38 by substantially 90° , and

25   converged by the objective lens 39 onto the object O
fixed on the X-Y table 21. Part of the light deflected
by the second translucent mirror 38 and directed to the

object O is reflected by the third translucent mirror 51 to the reference mirror 52.

The X-Y table 21 retaining the object O thereon is vertically moved at a predetermined speed (which corresponds to an interval t_2 between successive emissions of light from the first and second flash lamps 31 and 32) by vertically moving the vertical movement mechanism 22 under the control of the image processing unit 6 in synchronism with the emission interval t_2 of each flash lamp.

The light reflected from the object O is directed to the camera 42. At the third translucent mirror 51, the light reflected from the object O and the light reflected and returned from the reference mirror 52 are synthesized into interference light.

The interference light formed by the light reflected from the object O and the light reflected from the reference mirror 52 passes through the second translucent mirror 38 and is converged by the relay lens 41 onto the light receiving surface (not shown) of the two-dimensional camera 42 that can record each intensity-distribution image of interference light formed by light beams of different wavelengths, in a time series manner in relation to a corresponding wavelength.

The interference light converged on the light receiving surface of the camera 42 is subjected to

photoelectric conversion and then supplied to the image
processing unit 6. At this time, the camera 42 outputs
a plurality of images in accordance with the movement
of the movement table 21 executed in the direction of

5   the flash light for the predetermined interval t_2.
Each image includes two different images formed by
light of the wavelengths λ_1 and λ_2.

The intensity of interference light varies in
accordance with the movement of the X-Y table 21

10   moved by the vertical movement mechanism 22 at
a predetermined speed. The variations of the light
intensity indicate the surface profile features of the
object. Accordingly, the surface profile of the object
can be obtained by analyzing the pattern of

15   interference light picked up by the camera 42.

Further, the above-described profile measurement
apparatus 1 uses light beams of predetermined
wavelengths, i.e., the first and second wavelengths λ_1
and λ_2 close to each other, contained in white

20   light emitted by the two flash lamps 31 and 32.
Therefore, concerning an interference light intensity
for any selected point of the object O picked by the
camera 42 while the X-Y table 21 is being moved at
a predetermined speed, different intensity change

25   patterns of interference light, which is formed by
light beams of first and second wavelengths λ_1 and λ_2,
are obtained with lapse of time even if the optical

- path difference is same, as will be described later
with reference to FIG. 4.

FIG. 3 is a schematic view useful in explaining
a phenomenon detected by the profile measurement
5   apparatus 1, in which different two points of the
object O picked by the camera 42 have different optical
path differences A and B (the actual height differences
are A/2 and B/2, since the apparatus of FIG. 1 employs
a reflection type interferometer, and the detected
10   optical path differences are detected to be twice the
respective height differences).

As shown in FIG. 3, when the X-Y table 21 has been
vertically moved at a constant speed by the vertical
movement mechanism 22, a conjugate image obtained by
15   the reference mirror 52 is formed at a position (level)
indicated by the broken line. On the other hand, the
surface of the object O upwardly passes through the
position of the conjugate image. Concerning different
portions (e.g. A and B) of the object O, the surface of
20   the object O passes a vertical position, at which the
optical path difference is zero, at different time
points.

FIG. 4 is a view useful in explaining the
relationship between the optical path difference and
25   light intensity shown in FIG. 3, showing envelopes of
sine wave intensity variations determined from the
limited coherent of interference light.

For example, the speed of the movement of the X-Y table 21 driven by the vertical movement mechanism 22, i.e., the movement speed of the vertical movement mechanism 22, is set as the phase shift corresponding to the time required for the camera 42 to pick up one set of images (images corresponding to the wavelengths λ_1 and λ_2). Specifically, it is set to $2\pi \times n$ (n is an integer not less than 1, and set at 2 in this case) $+\alpha$ (α falls within a range of $\pm\pi/2 \pm \pi/4$).

Further, if the two flash lamps 31 and 32 are made to emit light for a predetermined interval t_1, e.g. 10 microsec., in synchronism with the timing for image pickup by the camera 42, the camera 42 picks up one set of images at time points corresponding to optical path differences (1), (2), (3), (4), (5), …. As a result, the camera 42 picks up interference light images (interference patterns) of varying light intensities based on the wavelengths λ_1 and λ_2. In FIG. 4, the broken curve indicates an image based on the wavelength λ_1, and the solid curve indicates an image based on the wavelength λ_2. Since the wavelengths λ_1 is different from λ_2, an allowable range of $\pm\pi/4$ is imparted to $2\pi \times n \pm \pi/2$ serving as a phase to be changed when the camera 42 picks up one set of images.

For example, supposing that the light intensity of a j-th image is I_j, and the phase shift amount is α, the phase value ϕ_j and amplitude (corresponding to

half the changing width of a light intensity) A_j of
an interference pattern picked by the camera 42 are
given by

$$\phi_j = \arg[2i\sin\alpha(I_{j-1} - I_{j+1}) + (2I_j - I_{j+2} - I_{j-2})]$$

5   (i is an imaginary number term)

$$A_j = \frac{1}{2}\sqrt{4\sin^2\alpha(I_{j-1} - I_{j+1})^2 + (2I_j - I_{j+2} - I_{j-2})^2}$$

The interference pattern corresponds to a signal
output from the camera 42 and to the j-th image formed
by the light beams of the wavelength λ_1 and λ_2.

10   After that, among the images (interference
patterns) formed by the light beam of the wavelength
λ_1, a k-th image signal that has a maximum amplitude
A_1 is detected and a corresponding phase value ϕ_j is
detected.

15   As shown in FIG. 5, the phase value ϕ_j ranges
from $-\pi$ to π. In FIG. 5, the broken curve indicates
an image based on the wavelength λ_1, while the solid
curve indicates an image based on the wavelength λ_2.

        As illustrated in FIG. 5, the phase value ϕ_j

20 changes sharply in proportion to the optical path
difference. It is evident from FIG. 5 that a number of
optical path differences exist which provide
a particular phase value ϕ_j. In other words, the
optical path difference cannot be determined directly

25 from the phase value ϕ_j. The phase difference between
the phase of the light beam of the wavelength λ_1 and
that of the light beam of the wavelength λ_2 changes

more gently than the optical path difference.
Accordingly, one optical path difference can be
determined from the phase difference.

As shown in FIG. 6, the inclination of changes in
the phase difference with respect to the optical path
difference is small, and therefore if the resultant
phase difference contains noise, an accurate optical
path difference cannot be obtained since the
inclination is small. However, the use of both the
phase difference and the phase value based on the
wavelength λ_1 (or λ_2) enables a more accurate optical
path difference to be obtained when the k-th image has
been picked up.

On the other hand, concerning the amplitude A_j,
its accuracy is actually low. From this, it is merely
understood that the optical path difference is around
zero. Therefore, it is difficult to correctly
determine the peak position of each envelope of FIG. 4.
However, it is possible to discriminate areas (areas C
and D in FIGS. 4 to 6) in which the difference in the
phase values of the light beams of the wavelengths λ_1
and λ_2 is 2π, and accordingly which appear to have the
same phase difference.

Using the above features, the reflection surface
position of each pixel can be calculated from the
amount of movement of the X-Y table 21 in an image
pickup cycle, an image number k, and the optical path

- difference assumed when the k-th image is picked up. From this calculation result, the surface profile of the object O can be obtained.

In other words, the present invention is

5   characterized in that a series of images based on each light wavelength are extracted in the order of recording from a number of images recorded by the camera 42; the phase value of a light beam of each wavelength used to record a j-th image, and the

10   amplitude of sine-wave type variations in an interference signal are calculated using the phase shift method; and a k-th image, in which the amplitude of the sine-wave type variations is large (i.e., the optical path difference is nearly zero), is detected

15   for each pixel of an object picked up by the camera 42, thereby extracting the phase value of a light beam of each wavelength that forms the image.

Since the difference (phase difference) between the phase values of two light beams of different

20   wavelengths is substantially proportional to the optical path difference as shown in FIG. 6, a rough optical path difference is calculated from the phase difference, and then a more accurate optical path difference is calculated from the calculated value and

25   the phase value of a light beam of the wavelength λ_1 or λ_2, thereby obtaining an image number k and an accurate optical path difference assumed when a k-th

image is picked up.

[Example 1]

A description will now be given of measurement
results obtained by measuring the profile of a certain
5   polished surface using the profile measurement
apparatus of FIG. 1.   The phase shift amount employed
was $4\pi - \pi/2$.

FIG. 7 shows the relationship between numbers
assigned to interference images corresponding to
10   a certain pixel picked by the camera 42, and variations
in the intensity of interference light.   Broken curve a
indicates the intensity of light of the wavelength λ_1,
while solid curve b indicates the intensity of light of
the wavelength λ_2.   Further, curve c of the one-dot
15   chain line indicates variations in the amplitude A_j.

First, a k-th image having a maximum amplitude is
obtained from FIG. 7.

Subsequently, as shown in FIG. 8, a change amount
a (which indicates a change in the phase value of light
20   of the wavelength λ_1), a change amount b (which
indicates a change in the phase value of light of
the wavelength λ_2), and the phase difference ϕ_{12}
(the difference between the phase values of the light
of the wavelengths λ_1 and λ_2) are calculated from data
25   concerning the k-th image having a maximum amplitude,
and images located near the k-th image.   The horizontal
coordinate of FIG. 8 indicates the relative image

- number, and [2] indicates the k-th image (image with number k) obtained from FIG. 7. Accordingly, [1] of the horizontal coordinate indicates an image number k-1, and [3] an image number k+1.

It is understood from FIG. 8 that the phase shift amount α of the light of the wavelength λ_1 (indicated by the broken curve $\underline{a}$) is substantially $\pi/2$ (a constant), while the phase shift amount α of the light of the wavelength λ_2 (indicated by the solid curve $\underline{b}$) falls within a range of $3\pi/4 - \pi/2$.

Furthermore, it is understood from FIG. 8 that the phase difference ϕ_{12} considerably changes in accordance with the image number, and therefore, the optical path difference significantly changes.

FIGS. 9 to 11 show a state in which light (interference light) reflected from an object O and picked up by the camera 42 is being processed, and the shape of the object O resulting from the processing.

FIG. 9 shows a k distribution of k-th image having a maximum amplitude and included in each pixel of an image picked by the camera 42. FIG. 10 shows a distribution of optical path differences (calculated values) assumed when the k-th images have been picked up.

FIG. 11 shows the profile calculated from the movement amounts of the X-Y table 21, the distribution of the k-th images shown in FIG. 9, and the optical

path differences of FIG. 10. In FIG. 11, surface

irregularities indicate noise contained in an image

signal, which can be almost eliminated by increasing

the amount of light (the energy of light of

5   a predetermined wavelength passing through the

band-pass filter) emitted from each light source (e.g.

flash lamp).

As shown in FIG. 11, a three-dimensionally

displayed result, which is obtained simply by combining

10   data based on the k-values (FIG. 9) and the optical

length (FIG. 10) calculated for each pixel of an image

picked by the camera, is sufficiently faithful to the

profile of the polished surface. From this, it is

evident that the profile measuring method of the

15   present invention can correctly measure the surface of

an object O, even if the surface has a step.

For comparison, the profile of an object O

obtained only using the known phase shift method is

shown in FIG. 12. In the case of FIG. 12,

20   no consideration is given to the calculation of

a maximum amplitude for each pixel.

As a result, the phase values increase and

decrease at a cycle of 2π in the X-direction, even if

the surface of the object O is actually smooth.

25   This discontinuity is usually eliminated by a certain

process on the assumption that the to-be-measured

surface is smooth, thereby providing a final profile.

Accordingly, the profile of a step, if there is one,
cannot be measured.

As described above, in the profile measuring
method of the invention, the phase value of

5   an interference image created by light reflected from
an object and light reflected from the reference mirror
is calculated using the phase shift method, in which
one of the interference light paths is changed stepwise
to thereby shift the phase of an interference signal.

10   From the resultant phase value, the optical path
difference between the interference light paths is
calculated, to thereby obtain the surface profile of
the object. In this method, the phase shift amount
can be set to $2\pi \times n$ (n is an integer not less than 1)

15   $+\alpha$ ($|\alpha|$ falls within a range of from $+\pi/2-\pi/4$ to
$+\pi/2+\pi/4$). This value is up to several tens of times
higher than the currently used shift amount of $\pi/2$ or
$\pi/3$.

Moreover, two flash light sources are used to

20   substantially simultaneously (with almost no time lag)
emit respective light beams at an interval of a phase
change, thereby providing instant illumination beams of
the wavelengths λ_1 and λ_2. A two-dimensional camera
is used to record, in a time series manner, the light

25   intensity image of interference light corresponding to
each wavelength, obtained at the time of phase
shifting. Series of images corresponding to each

wavelength are extracted in the order of recording from a number of recorded images, whereby the phase value of a light beam of each wavelength and the amplitude of sine-wave type variations in interference signal

5   (FIG. 4), which are obtained when, for example, a j-th image contained in the extracted images has been recorded, are calculated using the phase shift method. For each pixel included in a to-be-measured area picked by the two-dimensional camera, a k-th image that has a

10   maximum amplitude (the optical path difference is close to zero) is obtained, thereby detecting the phase value of a light beam of each wavelength forming the k-th image, and calculating an approximate optical path difference from the phase difference between the light

15   beams of the wavelengths. From the calculated phase difference and the phase value of the light beam of the wavelength λ_1 or λ_2, a more accurate optical path difference is calculated. The acquisition of the k-th image and the accurate optical path difference assumed

20   when the k-th image has been picked up enables the surface profile of an object to be measured with high accuracy on the basis of a plurality of interference images picked with a phase shift amount of not less than π.

25   In other words, the movement table is moved in units of phase shift amounts, thereby calculating a k- th image with a maximum amplitude for each pixel,

and calculating an optical path difference assumed when the k-th image is picked up. Both the calculatings are repeated for all the pixels in a to-be-measured area, which enables object surface profiles to be accurately

5   measured.

As described above, the profile measurement apparatus of the invention can measure the surface profile of an object, which includes fine irregularities, at a speed up to several tens of times

10 the conventional speed, while maintaining a fine resolving power. Further, it can provide a wide measurement range that cannot be realized by the known phase shift method.

Additional advantages and modifications will

15 readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details and representative embodiments shown and described herein. Accordingly, various modifications may be made without departing from the

20 spirit or scope of the general inventive concept as defined by the appended claims and their equivalents.